APPENDIX **B**

EFFECTS OF CONVERTING RURAL INTERSECTIONS FROM STOP TO SIGNAL CONTROL

INTRODUCTION

The analysis undertaken examined the safety impacts of converting rural intersections from stop-controlled operation to signal control. The basic objective was to estimate the change in crashes. Target crash types considered included:

- All crash types
- Right angle (side impact) crashes
- Left turn opposing (one vehicle oncoming) crashes
- Rear end crashes

The change in crash frequency was analyzed as well as the changes in overall economic costs, recognizing that different crash types and severity levels have different economic costs. Also developed were models for signalized intersections to explore the feasibility of using such models to evaluate the potential benefits of a proposed signal conversion.

Meeting the objectives placed some special requirements on the data collection and analysis tasks. These were:

- The need to select a large enough sample size to detect, with statistical significance, what may be small changes in safety for some crash types
- The need to carefully select comparison or reference sites
- The need to properly account for traffic volumes changes
- The need to conduct a multi-jurisdictional study to improve reliability of the results and facilitate broader applicability of the products of the research.

Geometric, traffic volume and accident data were acquired for the States of California (1993-2002) and Minnesota (1991-2002) to facilitate the analysis. The Highway Safety Information System (HSIS) provided these data.

Subsequently, a dataset of high-speed rural intersections in Iowa which were converted from stop- to signal-controlled was acquired. A reference group of similar sites was also provided. These data were limited in that time trends could not be accounted for but were used to reaffirm the results from the analysis of California and Minnesota data.

METHODOLOGY

Analysis of Crash Frequency

The general analysis methodology used is different from those used in the past, benefiting from significant advances made in safety analysis for the conduct of observational before-after studies, which culminated in a 1997 landmark book by Hauer. (*1*) That book also provides guidance on study design elements such as size and selection criteria for treatment and comparison groups and the pooling of data from diverse sources. All these are crucial elements in successfully conducting a study to obtain results that would have wide applicability.

Specifically, the analysis:

- Properly accounts for regression-to-the-mean
- Overcomes the difficulties of using crash rates in normalizing for traffic volume differences between the before and after periods
- Reduces the level of uncertainty in the estimates of safety effect
- Provides a foundation for developing guidelines for estimating the likely safety consequences of contemplated signal conversion
- Properly accounts for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions

In the EB approach the change in safety for a given crash type at an intersection is given by:

$$\lambda - \pi \qquad \text{B1)}$$

where λ is the expected number of crashes that would have occurred in the after period without signal conversion and π is the number of reported crashes in the after period.

In estimating λ, the effects of regression to the mean and changes in traffic volume were explicitly accounted for using safety performance functions (SPFs) relating crashes of different types and severities to traffic flow and other relevant factors for each jurisdiction *based on unconverted stop-controlled intersections*. Annual SPF multipliers were calibrated to account for the temporal effects on safety of variation in weather, demography, crash reporting and so on.

In the EB procedure, the SPF is used to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to the one being analyzed. The sum of these annual SPF estimates (P) is then combined with the count of crashes (x) in the before period at a treatment site to obtain an estimate of the expected number of crashes (m) before signal conversion. This estimate of m is:

$$m = w_1(x) + w_2(P), \qquad \text{B2)}$$

where the weights w_1 and w_2 are estimated from the mean and variance of the regression estimate as:

$$w_1 = P/(P + 1/k) \qquad \text{B3)}$$

$$w_2 = 1/k(P + 1/k), \qquad \text{B4)}$$

where k is a constant for a given model and is estimated from the SPF calibration process with the use of a maximum likelihood procedure. (In that process, a negative binomial distributed error structure is assumed with k being the dispersion parameter of this distribution.)

A factor is then applied to m to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period divided by P, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of λ. The procedure also produces an estimate of the variance of B, the expected number of crashes that would have occurred in the after period without signal conversion.

The estimate of λ is then summed over all intersections in a treatment group of interest (to obtain λ_{sum}) and compared with the count of crashes during the after period in that group (π_{sum}). The variance of λ is also summed over all sections in the treatment group.

The Index of Effectiveness (θ) is estimated as:

$$\theta = (\pi_{sum}/\lambda_{sum}) \,/\, \{1 + [Var(\lambda_{sum})/\lambda_{sum}^2]\}. \qquad \text{B5)}$$

The standard deviation of θ is given by:

$$Stddev(\theta) = [\theta^2\{[Var(\pi_{sum})/\pi_{sum}^2] + [Var(\lambda_{sum})/\lambda_{sum}^2]\} \,/\, [1 + Var(\lambda_{sum})/\lambda_{sum}^2]^2]^{0.5} \qquad \text{B6)}$$

The percent change in crashes is in fact $100(1-\theta)$; thus a value of $\theta = 0.7$ with a standard deviation of 0.12 indicates a 30 percent reduction in crashes with a standard deviation of 12%.

Analysis of Economic Costs

The general analysis methodology used to define the economic effects of signal conversion closely parallels the methodology used for crash frequency. Here, instead of the difference between the crashes “expected without treatment” versus “observed with treatment” in the after period, the measure of effectiveness is the difference between the net economic costs “expected without treatment” and “observed with treatment” in the after period. The methodology described below was taken from the 2005 report by Council et al. (*2*)

For simplicity, the theory is presented for estimating the change in crash costs over all treatment sites in a jurisdiction, *for a specific crash type*, aggregated over all KABCO subgroups (e.g., two subgroups K+A+B+C, O). The crash types of interest are right-angle, rear-end, and other (i.e. other than rear-end and right-angle). The following notation is used:

$\text{Cost}_{\text{B}i}$ = cost of crashes in KABCO subgroup *i* actually occurring at the treatment sites in the before period

Λ_{costA} = cost of crashes actually occurring at the treatment sites in the jurisdiction in the after period

$\text{VAR}\{\text{Cost}_\text{B}\}$ = variance of the cost of crashes in the before period

$\text{VAR}\{\Lambda_{\text{costA}}\}$ = variance of the cost of crashes in the after period

Π_{costA} = expected cost of crashes in the after period over all treatment sites had there been no treatment (after correcting for regression to the mean and traffic volume and other differences between before and after periods)

$\text{VAR}\{\Pi_{\text{costA}}\}$ = variance of the expected cost of crashes over all treatment sites in the after period without RLC

B_i = observed number of crashes in KABCO subgroup *i* over all treatment sites in the before period

Π_i = expected number of crashes in KABCO subgroup *i* over all treatment sites in the after period without treatment (after correcting for regression to the mean and traffic volume and other differences between before and after periods). These are derived for the crash frequency analysis.

The estimated change in crash costs is

$$\Phi_{cost} = \Pi_{costA} - \Lambda_{costA} \qquad \text{B7)}$$

The variance of change in crash costs in

$$\mathrm{Var}\{\Phi_{cost}\} = \mathrm{Var}\{\Pi_{costA}\} + \mathrm{Var}\{\Lambda_{costA}\} \qquad \text{B8)}$$

The cost modification factor is

$$\theta_{cost} = (\Lambda_{costA}/\ \Pi_{costA})\ /[1+ (\mathrm{VAR}\{\Pi_{costA}\}/\Pi_{costA}^2)] \qquad \text{B9)}$$

The variance of cost modification factor is given by

$$\mathrm{VAR}\{\theta_{cost}\}= \theta_{cost}^2\{[\mathrm{VAR}(\Lambda_{costA})/\Lambda_{costA}^2] + \mathrm{VAR}(\Pi_{costA})/\Pi_{costA}^2]\}/ [1+ (\mathrm{VAR}\{\Pi_{costA}\}/\Pi_{costA}^2)]^2 \qquad \text{B10)}$$

It remains to say how estimates were obtained for the 4 terms, Λ_{costA}, VAR$\{\Lambda_{costA}\}$, Π_{CostA} and VAR$\{\Pi_{costA}\}$. Approximate methods used are given below.

The value of Λ_{costA} (i.e., actual after crash cost) was estimated by summing the individual PIRE costs for each crash in the after period over all treated intersections in the jurisdiction. The value of VAR[Λ_{costA}] was estimated by summing the variance for each individual cost of the crashes of interest in the after period.

$\Pi_{costA,}$ (i.e., the expected after cost without treatment) was estimated for a KABCO subgroup by first estimating an expected cost for each site as the product of Π_i = expected number of crashes in the KABCO subgroup and the PIRE unit economic cost for the crash type, KABCO subgroup and speed limit category. These were then summed over all treatment sites and KABCO subgroups to get $\Pi_{costA.}$

VAR$\{\Pi_{costA}\}$ for each site and subgroup was taken as product of Π_i and the PIRE unit variance for the crash type, KABCO subgroup and speed limit category. These variances were then summed over all sites and KABCO subgroups. This is an approximation that likely underestimates the variance, given that there is variance in the EB estimates of the expected number of crashes without treatment. However, the PIRE unit cost variances are also approximations in that they do not include all components (e.g. variance in medical costs by diagnosis). Fortunately, the point estimates of the economic effects, which are of primary interest in this analysis, are quite insensitive to VAR$\{\Pi_{costA}\}$.

As noted, the theory so far applies for a given crash type of the three comprising all crashes. To obtain estimates of economic effect for all crash types combined, Λ_{costA},

$VAR\{\Lambda_{costA}\}$, Π_{CostA} and $VAR\{\Pi_{costA}\}$ are first determined for each crash type as outlined above and then summed over all crash types before applying Equations 7 to 10.

It is infeasible to analyze each crash type separately due to small numbers of many crash types and because crash costs are not available for all crash types. For this reason, total, right-angle and rear-end crashes were analyzed separately and a cost for “other” crashes derived by subtracting the right-angle and rear-end costs from the total costs. Of particular note is that left-turn opposing crashes are included in the “other” group because costs are not available for this crash type. The costs estimates for “other” right-angle and rear-end are used to estimate the economic effects of signal conversion.

The crash cost data came from the 2005 FHWA report number titled “Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometrics.” (*3*) The report provides the mean and standard error of the comprehensive cost per crash for various crash types disaggregated by various combinations of maximum severity level on the KABCO scale and also disaggregated by speed limit (>=50, <=45). The disaggregation by speed limit was an attempt to control for urban versus rural environment, a variable not available in the data used to derive the cost estimates. The analysis used estimates for the >=50 mph speed category to reflect the rural conditions of the treatment sites. Table B-1 shows the unit crash costs used in this study.

Table B-1. Unit crash costs used in the analysis.

Control Type	Severity Level	Right Angle Cost (s.e)	Rear End Cost (s.e.)	Other Cost (s.e.)
Signal	Injury (s.e)	$126,878 $9,619	$52,276 $13,794	$126,878 $9,619
	PDO (s.e)	$8,544 $1,294	$5,901 $1,802	$8,544 $1,294
Stop Sign	Injury (s.e)	$199,788 $27,768	$34,563 $12,854	$199,788 $27,768
	PDO (s.e)	$5,444 $1,265	$3,788 $978	$5,444 $1,265
s.e. – standard error				

DATA COLLECTION

This section provides a summary of the databases acquired for California and Minnesota. These include data for intersections converted from stop-control to signalized, unconverted stop-controlled intersections and unconverted signalized intersections.

Table B-2 describes how the crash types analyzed were defined for California and Minnesota. Due to different crash related variables available in the data, the definitions were not strictly the same.

Table B-2. Definitions of intersection-related, right-angle, rear-end and left-turn crashes used in the analyses for each jurisdiction.

California

Intersection Related - All crashes at or within 250 ft. of intersection.
Right-Angle – Defined as broadside with no vehicles making a left-turn.
Rear End – Defined as rear-end with no vehicles making a left-turn.
Left-Turn – One vehicle turning left and one vehicle proceeding straight from opposite direction.

Minnesota

Intersection Related - Crashes at or within 250 ft. of intersection and defined as at intersection or intersection-related.
Right-Angle – Defined as right-angle.
Rear End – Defined as rear-end.
Left-Turn – Defined as left-turn into oncoming traffic.

Iowa

Intersection Related - All crashes at or within 150 ft. of intersection.
Right-Angle – Defined as broadside, angle or oncoming left-turn.
Rear End – Defined as rear-end.
Left-Turn – Left-turn oncoming traffic included in right-angle.

California Data

In California, the data were split into four groups with sufficient sites for building the required SPFs. These are:

- stop-controlled 3 legged with 2 lanes on major road
- stop-controlled 4 legged with 2 lanes on major road
- stop-controlled 4 legged with 4 lanes on major road
- signalized 4 legged

The following tables summarize the data for the:

- Converted stop-controlled intersections
- Unconverted (reference) stop-controlled intersections, and
- Unconverted (reference) signalized intersections.

Table B-3. Converted stop-controlled intersections (3-leg with 2 lanes on major).

Number of Sites = 4			
Variable	Mean	Minimum	Maximum
Years before	1	1	6
Years after	6	4	9
Crashes/site-year before	6.458	1	153
Crashes/site-year after	3.525	0.57	7.778
Right-angle crashes/site-year before	0.083	0	0.33
Right-angle crashes/site-year after	0	0	0
Rear-end crashes/site-year before	0.083	0	0.167
Rear-end crashes/site-year after	0.215	0	0.5
Left-turn crashes/site-year before	3.125	0.33	10.33
Left-turn crashes/site-year after	0.146	0	0.33
Major road AADT before	12975	5750	19100
Minor road AADT before	5613	201	10300
Major road AADT after	15105	7400	26945
Minor road AADT after	5638	201	10300

Table B-4. Converted stop-controlled intersections (4-leg with 2 lanes on major).

Number of Sites = 14			
Variable	Mean	Minimum	Maximum
Years before	4.286	1	8
Years after	5.714	2	9
Crashes/site-year before	3.303	0.125	8.6
Crashes/site-year after	3.280	0.667	9
Right-angle crashes/site-year before	0.964	0	2.5
Right-angle crashes/site-year after	0.379	0	1.667
Rear-end crashes/site-year before	0.198	0	0.75
Rear-end crashes/site-year after	0.173	0	0.5
Left-turn crashes/site-year before	0.886	0	3.25
Left-turn crashes/site-year after	0.727	0	3.25
Major road AADT before	10344	7400	18738
Minor road AADT before	2150	101	5280
Major road AADT after	11204	7762	21700
Minor road AADT after	2187	101	5280

Table B-5. Converted stop-controlled intersections (4-leg with 4 lanes on major).

Number of Sites = 10			
Variable	Mean	Minimum	Maximum
Years before	3.4	1	6
Years after	6.6	4	9
Crashes/site-year before	5.557	2.667	10.5
Crashes/site-year after	5.229	1.44	10.75
Right-angle crashes/site-year before	2.15	0	7
Right-angle crashes/site-year after	0.568	0	1.167
Rear-end crashes/site-year before	0.2	0	1
Rear-end crashes/site-year after	0.44	0	1.25
Left-turn crashes/site-year before	1.507	0	3
Left-turn crashes/site-year after	1.018	0	2.667
Major road AADT before	15958	7018	25666
Minor road AADT before	2716	600	9700
Major road AADT after	18235	7155	29750
Minor road AADT after	2790	600	9646

Table B-6. Unconverted (reference) stop-controlled intersections (3-leg with 2 lanes on major).

Number of Sites = 1405			
Variable	Mean	Minimum	Maximum
Years	10	10	10
Crashes/site-year	0.846	0	13.900
Right-angle crashes/site-year	0.018	0	0.600
Rear-end crashes/site-year	0.063	0	1.000
Left-turn crashes/site-year	0.171	0	8.700
Major road AADT	9019	2950	31450
Minor road AADT	554	100	10001

Table B-7. Unconverted (reference) stop-controlled intersections (4-leg with 2 lanes on major).

Number of Sites = 742			
Variable	Mean	Minimum	Maximum
Years	10	10	10
Crashes/site-year	1.390	0	9.40
Right-angle crashes/site-year	0.327	0	4.70
Rear-end crashes/site-year	0.1	0	1.80
Left-turn crashes/site-year	0.232	0	3.100
Major road AADT	8557	3101	28055
Minor road AADT	656	100	7800

Table B-8. Unconverted (reference) stop-controlled intersections (4-leg with 4 lanes on major).

Number of Sites = 183			
Variable	Mean	Minimum	Maximum
Years	10	10	10
Crashes/site-year	1.230	0	7.5
Right-angle crashes/site-year	0.280	0	3.500
Rear-end crashes/site-year	0.096	0	0.800
Left-turn crashes/site-year	0.245	0	2.300
Major road AADT	12441	3087	30500
Minor road AADT	592	100	6000

Table B-9. Annual accident frequencies for stop-controlled intersections (3-leg with 2 lanes on major).

Year	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**00**	**01**	**02**
TOTAL	1124	1135	1214	1134	1126	1138	1220	1209	1247	1233
RA	26	20	28	25	22	18	34	23	35	27
LT	200	225	222	219	226	268	257	288	233	263
RE	136	84	101	78	77	86	80	64	86	89
KABC	504	512	532	485	669	498	502	490	524	509
KABC_RA	16	9	14	15	13	11	22	15	21	13
KABC_LT	105	112	125	107	116	139	129	146	121	124
KABC_RE	63	39	41	40	30	32	27	25	34	36
O	604	613	666	638	643	728	706	707	717	714
O_RA	10	10	14	10	9	7	12	8	14	14
O_LT	94	112	95	110	104	128	126	140	111	135
O_RE	73	43	60	38	45	54	53	38	52	53

Table B-10. Annual accident frequencies for stop-controlled intersections (4-leg with 2 lanes on major).

Year	93	94	95	96	97	98	99	00	01	02
TOTAL	1003	976	1011	946	1015	997	1007	1046	1146	1149
RA	271	231	225	233	241	246	225	233	233	260
LT	169	143	160	151	167	191	174	174	201	209
RE	111	79	76	59	71	60	65	74	84	69
KABC	475	477	452	463	489	464	458	472	488	500
KABC_RA	156	144	141	143	135	150	140	147	130	152
KABC_LT	91	83	72	88	85	96	88	87	102	108
KABC_RE	43	36	35	27	39	22	19	26	32	28
O	514	492	544	477	521	519	534	558	670	642
O_RA	112	85	82	90	105	94	83	85	133	107
O_LT	79	59	84	63	82	74	86	85	99	100
O_RE	64	43	39	32	32	38	45	46	52	41

Table B-11. Annual accident frequencies for stop-controlled intersections (4-leg with 4 lanes on major).

Year	93	94	95	96	97	98	99	00	01	02
TOTAL	231	180	211	203	205	248	252	231	252	238
RA	71	46	45	39	43	60	52	58	47	52
LT	51	29	45	35	36	59	55	37	53	49
RE	18	17	13	14	18	10	27	16	22	21
KABC	121	82	115	109	103	114	115	108	127	93
KABC_RA	42	25	27	27	27	40	31	37	29	33
KABC_LT	33	13	31	23	18	34	33	22	32	23
KABC_RE	10	6	6	8	8	1	9	6	8	6
O	108	98	96	94	102	133	137	119	124	146
O_RA	29	21	18	12	16	20	21	19	18	19
O_LT	18	16	14	12	18	25	22	15	21	26
O_RE	7	11	7	6	10	9	18	9	13	15

Table B-12. Unconverted (reference) signalized intersections (4-leg).

Number of Sites = 63			
Variable	Mean	Minimum	Maximum
Years	10	10	10
Crashes/site-year	4.6	0.1	20.0
Right-angle crashes/site-year	0.6	0.0	2.2
Rear-end crashes/site-year	2.1	0.0	11.2
Major road AADT	15,342	3,055	47,000
Minor road AADT	5,675	101	23,600

Minnesota Data

In Minnesota, the data were split into three groups with sufficient sites for building the required SPFs as follows:

- stop-controlled 3 legged
- stop-controlled 4 legged
- signalized 4 legged

The following tables summarize the data for the:

- Converted stop-controlled intersections
- Unconverted (reference) stop-controlled intersections, and
- Unconverted (reference) signalized intersections.

Table B-13. Converted stop-controlled intersections (3-leg).

Number of Sites = 2			
Variable	Mean	Minimum	Maximum
Years before	6.50	6.00	7.00
Years after	4.50	4.00	5.00
Crashes/site-year before	4.29	0.00	8.57
Crashes/site-year after	3.80	1.60	6.00
Right-angle crashes/site-year before	1.29	0.00	2.57
Right-angle crashes/site-year after	0.00	0.00	0.00
Rear-end crashes/site-year before	0.71	0.00	1.43
Rear-end crashes/site-year after	2.13	0.00	4.25
Left-turn crashes/site-year before	1.21	0.00	2.43
Left-turn crashes/site-year after	2.15	0.80	3.50
Major road AADT before	18361	18223	18498
Minor road AADT before	2068	602	3535
Major road AADT after	17278	17065	17491
Minor road AADT after	3666	1077	6255

Table B-14. Converted stop-controlled intersections (4-leg).

Number of Sites = 15			
Variable	mean	minimum	Maximum
Years before	4.53	1.00	8.00
Years after	6.53	3.00	10.00
Crashes/site-year before	12.64	3.88	28.00
Crashes/site-year after	8.90	2.00	20.20
Right-angle crashes/site-year before	6.41	1.50	15.50
Right-angle crashes/site-year after	2.22	0.67	6.20
Rear-end crashes/site-year before	2.01	0.25	14.00
Rear-end crashes/site-year after	2.05	0.00	10.00
Left-turn crashes/site-year before	2.11	0.00	4.50
Left-turn crashes/site-year after	4.36	0.40	9.43
Major road AADT before	13739	3261	29926
Minor road AADT before	2659	986	5210
Major road AADT after	17614	3327	38179
Minor road AADT after	5324	1759	18165

Table B-15. Unconverted (reference) stop-controlled intersections (3-leg).

Number of Sites = 522			
Variable	Mean	Minimum	Maximum
Years	12	12	12
Crashes/site-year	0.93	0	7.25
Right-angle crashes/site-year	0.26	0	3.75
Rear-end crashes/site-year	0.07	0	1.17
Left-turn crashes/site-year	0.26	0	3.17
Major road AADT	6710	1165	32645
Minor road AADT	989	196	12750

Table B-16. Unconverted (reference) stop-controlled intersections (4-leg).

Number of Sites = 736			
Variable	Mean	Minimum	Maximum
Years	12	12	12
Crashes/site-year	1.96	0	24.7
Right-angle crashes/site-year	0.97	0	16.6
Rear-end crashes/site-year	0.13	0	5.8
Left-turn crashes/site-year	0.38	0	14.7
Major road AADT	5538	1173	31074
Minor road AADT	902	194	18774

Table B-17. Annual accident frequencies for stop-controlled intersections (3-leg).

Year	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**00**	**01**	**02**
TOTAL	409	473	472	493	435	466	451	498	468	601	532	524
RA	93	115	110	139	122	159	141	139	119	138	164	170
LT	26	38	31	39	25	42	28	28	35	44	42	37
RE	120	143	139	133	125	134	109	134	139	200	139	118
KABC	203	195	203	215	189	221	194	273	203	279	238	227
KABC_RA	62	54	70	66	64	77	77	84	55	96	95	89
KABC_LT	10	18	15	17	15	23	16	16	18	25	16	14
KABC_RE	61	55	72	62	57	71	38	73	61	66	62	45
O	206	278	269	278	246	245	257	225	265	322	294	297
O_RA	31	61	40	73	58	82	64	55	64	42	69	81
O_LT	16	20	16	22	10	19	12	12	17	19	26	23
O_RE	59	88	67	71	68	63	71	61	78	134	77	73

Table B-18. Annual accident frequencies for stop-controlled intersections (4-leg).

Year	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**00**	**01**	**02**
TOTAL	1208	1196	1348	1351	1388	1465	1487	1459	1630	1621	1597	1585
RA	577	586	661	679	681	734	693	755	824	780	806	834
LT	99	72	78	91	70	99	64	120	112	108	100	91
RE	221	219	274	263	294	269	291	263	311	364	309	297
KABC	585	582	667	667	675	722	713	708	828	790	820	735
KABC_RA	355	308	384	384	405	414	435	461	506	462	505	454
KABC_LT	50	33	44	57	20	58	26	50	55	60	53	57
KABC_RE	76	123	128	126	130	131	116	105	122	149	146	120
O	623	614	681	684	713	743	774	751	802	831	777	850
O_RA	222	278	277	295	276	320	258	294	318	318	301	380
O_LT	49	39	34	34	50	41	38	70	57	48	47	34
O_RE	145	96	146	137	164	138	175	158	189	215	163	177

Table B-19. Unconverted (reference) signalized intersections (4-leg).

Number of Sites = 21			
Variable	Mean	Minimum	Maximum
Years	12	12	12
Crashes/site-year	7.1	1.1	24.7
Right-angle crashes/site-year	2.3	0.1	6.5
Rear-end crashes/site-year	2.7	0.5	14.7
Major road AADT	14,780	1,440	31,074
Minor road AADT	4,316	66	18,774

Iowa Data

In Iowa, the data were split into two groups with sufficient sites for building the required SPFs as follows:

- stop-controlled 3 legged
- stop-controlled 4 legged

The following tables summarize the data for the:

- Converted stop-controlled intersections, and
- Unconverted (reference) stop-controlled intersections.

Table B-20. Converted stop-controlled intersections (3- and 4-leg).

Number of Sites = 19			
Variable	Mean	Minimum	Maximum
Years before	3	3	3
Years after	3	3	3
Crashes/site-year before	4.30	0.00	18.00
Crashes/site-year after	4.21	0.67	11.00
Right-angle crashes/site-year before	2.00	0.00	7.67
Right-angle crashes/site-year after	1.18	0.00	5.67
Rear-end crashes/site-year before	0.81	0.00	4.67
Rear-end crashes/site-year after	1.79	0.00	4.33
Major road AADT before	12,367	6,400	20,600
Minor road AADT before	2,154	690	4,800
Major road AADT after	13,119	4,090	21,500
Minor road AADT after	2,516	1,140	7,900

Table B-21. Unconverted (reference) stop-controlled intersections (3- and 4-leg).

Number of Sites = 59			
Variable	Mean	Minimum	Maximum
Years	3	3	3
Crashes/site-year	0.79	0.00	9.67
Right-angle crashes/site-year	0.44	0.00	4.33
Rear-end crashes/site-year	0.22	0.00	5.00
Major road AADT	10,566	5,600	20,600
Minor road AADT	587	5	3,500

DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS (SPFS)

This section presents the safety performance functions (SPFs) developed. Generalized linear modeling was used to estimate model coefficients using the software package SAS and assuming a negative binomial error distribution, all consistent with the state of research in developing these models.

As noted earlier, in specifying a negative binomial error structure, the "dispersion" parameter, *k*, which relates the mean and variance of the regression estimate, is iteratively estimated from the model and the data. The value of *k* is such that the smaller its value the better a model is for a given set of data.

California Stop-Controlled Intersections

For California, separate SPFs were successfully calibrated for all, right-angle, left-turn and rear-end crash types. Separate SPFs for injury (K, A, B and C on the KABCO scale) and PDO (O) severities for these crash types however could not be calibrated. Severity factors for KABC and O severity crashes were applied as a multiplier to the total severity models.

Table B-22. SPFs for California intersections (3-legs with 2 lanes on major approach).

	All	**Right-Angle**	**Left-Turn**	**Rear-End**
Model	2	1	2	1
LN(α) **(standard error)**	-9.3212 (0.408)	-11.2899 (0.7418	-13.6715 (0.716)	-12.8039 (0.620)
β_1 **(standard error)**	1.1125 (0.046)	0.6727 (0.079	1.4828 (0.080)	1.3077 (0.0695
β_2 **(standard error)**	0.3248 (0.023)	0.4831 (0.037	0.5711 (0.037)	0.1789 (0.034)
KABC Severity Factor	0.44	0.12	0.51	0.30
O Severity Factor	0.56	0.88	0.49	0.70
Dispersion	0.564	1.083	1.192	1.025
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$		**Model 2:** $E\{\kappa\} = \alpha(Maj + Min)^{\beta_1}\left(\frac{Min}{Maj + Min}\right)^{\beta_2}$		

Table B-23. SPFs for California intersections (4-legs with 2 lanes on major approach).

	All	Right-Angle	Left-Turn	Rear-End
Model	1	1	1	2
LN(α) **(standard error)**	-9.1488 (0.554)	-10.2351 (0.9337	-13.2906 (0.918)	-13.6527 (0.7938)
β_1 **(standard error)**	0.7191 (0.060)	0.5707 (0.099	0.8215 (0.095)	1.4201 (0.088)
β_2 **(standard error)**	0.4813 (0.028)	0.6978 (0.047	0.7635 (0.046)	0.1857 (0.041)
KABC Severity Factor	0.46	0.35	0.52	0.22
O Severity Factor	0.54	0.65	0.48	0.78
Dispersion	0.483	1.128	0.910	0.726
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$		**Model 2:** $E\{\kappa\} = \alpha(Maj + Min)^{\beta_1}\left(\frac{Min}{Maj + Min}\right)^{\beta_2}$		

Table B-24. SPFs for California intersections (4-legs with 4 lanes on major approach).

	All	Right-Angle	Left-Turn	Rear-End
Model	1	1	2	1
LN(α) **(standard error)**	-9.6509 (1.191)	-10.5908 (1.645)	-16.6692 (2.302)	-15.2190 (1.803)
β_1 **(standard error)**	0.7693 (0.116)	0.6033 (0.247)	1.8023 (0.265)	1.5371 (0.200)
β_2 **(standard error)**	0.4262 (0.069)	0.6483 (0.097)	0.5590 (0.125)	0.2919 (0.091)
KABC Severity Factor	0.48	0.34	0.58	0.16
O Severity Factor	0.52	0.66	0.42	0.84
Dispersion	0.645	1.121	1.525	0.709
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$		**Model 2:** $E\{\kappa\} = \alpha(Maj + Min)^{\beta_1}\left(\frac{Min}{Maj + Min}\right)^{\beta_2}$		

Minnesota Stop-Controlled Intersections

For Minnesota, separate SPFs were successfully calibrated for all, right-angle, left-turn and rear-end crash types. Separate SPFs for injury (KABC) and PDO (O) severities were also successfully calibrated for these crash types.

Table B-25. Total crash SPFs for Minnesota intersections (3-legs).

	All	Right-Angle	Left-Turn	Rear-End
Model	1	1	1	1
LN(α) **(standard error)**	-8.699 (0.5249)	-13.2492 (0.8914)	-11.9558 (1.4210)	-11.4823 (0.9769)
β₁ **(standard error)**	0.4969 (0.0501)	0.7224 (0.0838)	0.2920 (0.1272)	0.7602 (0.0926)
β₂ **(standard error)**	0.6243 (0.0508)	0.8163 (0.0834)	0.9838 (0.1272)	0.5219 (0.0903)
Dispersion	1.760	0.725	0.332	0.597
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$				

Table B-26. Injury crash (KABC) SPFs for Minnesota intersections (3-legs).

	All	Right-Angle	Left-Turn	Rear-End
Model	1	1	2	1
LN(α) **(standard error)**	-8.8410 (0.6267)	-13.6898 (1.1175)	-12.5574 (1.9271)	-12.020 (1.1798)
β₁ **(standard error)**	0.4881 (0.0605)	0.7790 (0.1061)	1.2478 (0.2422)	0.7429 (0.1113)
β₂ **(standard error)**	0.5539 (0.0617)	0.7206 (0.1026)	0.9486 (0.1903)	0.5018 (0.1131)
Dispersion	1.265	0.457	0.207	0.439
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$		**Model 2:** $E\{\kappa\} = \alpha(Maj + Min)^{\beta_1}\left(\frac{Min}{Maj + Min}\right)^{\beta_2}$		

Table B-27. PDO crash SPFs for Minnesota intersections (3-legs).

	All	Right-Angle	Left-Turn	Rear-End
Model	1	1	2	1
LN(α) **(standard error)**	-9.6959 (0.6249)	-14.2233 (1.1838)	-12.3565 (1.9660)	-12.0749 (1.1461)
β₁ **(standard error)**	0.5033 (0.0585)	0.6376 (0.1083)	1.2188 (0.2472)	0.7518 (0.1076)
β₂ **(standard error)**	0.6878 (0.0589)	0.9498 (0.1126)	0.9016 (0.1954)	0.5350 (0.1012)
Dispersion	1.437	0.489	0.172	0.496
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$		**Model 2:** $E\{\kappa\} = \alpha(Maj + Min)^{\beta_1}\left(\frac{Min}{Maj + Min}\right)^{\beta_2}$		

Table B-28. Total crash SPFs for Minnesota intersections (4-legs).

	All	Right-Angle	Left-Turn	Rear-End
Model	1	1	1	1
LN(α) **(standard error)**	-8.850 (0.3624)	-9.9618 (0.5181)	-13.8148 (0.8869)	-12.5773 (0.6163)
β_1 **(standard error)**	0.5661 (0.0391)	0.4629 (0.0545)	0.7251 (0.0910)	0.9094 (0.0671)
β_2 **(standard error)**	0.6989 (0.0416)	0.8914 (0.0608)	0.8158 (0.0967)	0.5593 (0.0659)
Dispersion	2.040	1.021	0.481	0.852
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$				

Table B-29. Injury crash (KABC) SPFs for Minnesota intersections (4-legs).

	All	Right-Angle	Left-Turn	Rear-End
Model	1	1	1	1
LN(α) **(standard error)**	-8.8406 (0.4239)	-9.8111 (0.5758)	-13.0520 (1.1496)	-12.4421 (0.7998)
β_1 **(standard error)**	0.4843 (0.0457)	0.4146 (0.0607)	0.5636 (0.1249)	0.8891 (0.0902)
β_2 **(standard error)**	0.6509 (0.0493)	0.8543 (0.0687)	0.8099 (0.1289)	0.4465 (0.0864)
Dispersion	1.536	0.841	0.263	0.519
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$				

Table B-30. PDO crash SPFs for Minnesota intersections (4-legs).

	All	Right-Angle	Left-Turn	Rear-End
Model	1	1	1	1
LN(α) **(standard error)**	-10.1895 (0.4052)	-11.7869 (0.6279)	-16.1400 (1.2903)	-13.7922 (0.7328)
β_1 **(standard error)**	0.6441 (0.0432)	0.5349 (0.0644)	0.8923 (0.1246)	0.9119 (0.0773)
β_2 **(standard error)**	0.6953 (0.0453)	0.9345 (0.0706)	0.8385 (0.1358)	0.6472 (0.6472)
Dispersion	1.784	0.819	0.272	0.677
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$				

Iowa Stop-Controlled Intersections

For Iowa, a single SPF was successfully calibrated for all crash types. Percentage multipliers were applied for specific crash and severity types.

Table B-31. SPFs for Iowa intersections.

	All
Model	1
LN(α) **(standard error)**	-8.454 (3.948)
β_1 **(standard error)**	0.9564 (0.4240)
Dispersion	0.820
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$	
Crash Type	**Multiplier**
All KABC	0.42
All O	0.58
Right-Angle	0.57
Right-Angle KABC	0.48
Right-Angle O	0.52
Rear-End	0.27
Rear-End KABC	0.37
Rear-End O	0.63

Signalized Intersection Reference Group

For unconverted signalized intersections, the data from California and Minnesota were combined due to the small sample sizes. Even after combining the data, SPFs were only successfully calibrated for 4 legged intersections. Separate SPFs were calibrated for total (all), right-angle and rear-end crashes.

Model Forms:

1. $Acc/yr = \alpha(Major\ AADT)^{\beta_1}(Minor\ AADT)^{\beta_2}e^{state}$
2. $Acc/yr = \alpha(Major\ AADT \text{ x } Minor\ AADT)^{\beta}e^{state}$

Table B-32. Signalized intersection SPFs for California and Minnesota (4-legs).

	Total	Total RA	Total RE
	Model 1	**Model 2**	**Model 1**
LN(α) **(standard error)**	-4.0402 (0.1267)	-2.6105 (1.1337)	-6.7249 (1.4141.)
β_1 **(standard error)**	0.4430 (0.1297)	0.1976 (0.0655)	0.5791 (0.1425)
β_2 **(standard error)**	0.2237 (0.0520)		0.2718 (0.0572)
State **(standard error)**	CA = -0.5407 (0.1402) MN = 0	CA = -1.3866 (0.1725) MN = 0	CA = -0.3903 (0.1687) MN = 0
Dispersion	0.3733 (0.561)	0.5110 (0.0931)	0.5051 (0.0793)

RESULTS

Estimates of the index of effectiveness, θ, for the crash frequency analysis are given in Table B-33. Overall results are provided with and without the Iowa data because time trends were not accounted for Iowa and therefore the results may not be as reliable. The results show that there is a reduction in right-angle and left-turn opposing crashes and an increase in rear-end crashes, effects that are all in accord with conventional wisdom. Overall, there is a net reduction in crash frequency.

Table B-33. Crash frequency AMFs (standard errors in parentheses).

State	Total	Right-Angle	Left-Turn	Rear-End
CA	0.778 (0.061)	0.221 (0.036)	0.433 (0.065)	2.474 (0.373)
MN	0.488 (0.027)	0.228 (0.019)	0.374 (0.063)	1.300 (0.141)
IA	0.950 (0.085)	0.265 (0.053)	n/a	2.075 (0.323)
CA + MN	0.559 (0.025)	0.227 (0.017)	0.401 (0.047)	1.579 (0.142)
ALL	0.591 (0.025)	0.230 (0.017)	n/a	1.629 (0.136)

The opposite direction effects for rear-end and right-angle plus left-turn opposing crashes deserves attention from two perspectives. First, the extent to which the increase in rear-end crashes negates the benefits for right-angle and left-turn opposing crashes is unclear without further analysis. An examination of the changes in crash numbers is insufficient to provide clarity on this issue because of differences in severity levels between crash types and in the changes in these crashes following signal conversion. An examination of the economic costs of the changes based on an aggregation of rear-end, right-angle and “other” crash costs for various severity levels, which is intended to cast light on this issue, is the subject of the economic analysis, for which the theory was presented earlier in this appendix.

The second perspective of the opposing effects for the crash types is the implication that signal conversion would be most beneficial at intersections where there are relatively few rear-end crashes and many right-angle or left-turn opposing ones. To provide better guidance on this issue requires an examination of the net effect, i.e., the net economic benefit for intersections grouped by the numbers of each crash type.

Table B-34 shows the results for the economic analysis including a disaggregation by various characteristics of the converted intersections. Because the Iowa data did not include all of the same variables and does not account for time trends these data were not included. It should be remembered however that the crash count results indicated consistency between the Iowa results and those for California and Minnesota. The results indicate that:

- The benefits are greater and higher volume intersections
- The benefits are greater where the ratio of expected right-angle crashes to rear-end crashes is higher.
- For the data available, the benefits appear insensitive to the number of legs and lanes on the major road. It must be kept in mind however that the variation in these variables was poor.

Table B-34. Economic Cost AMFs.

Characteristic	Cost Theta	Cost Standard Error
All	0.265	0.001
California	0.315	0.002
Minnesota	0.247	0.001
3 leg	0.286	0.004
4 leg	0.264	0.001
2 lanes on major	0.265	0.002
4 lanes on major	0.265	0.001
AADT < 20,000	0.314	0.003
AADT > 20,000	0.253	0.001
Exp RA/Exp RE <=4.5	0.324	0.002
Exp RA/Exp RE >4.5	0.215	0.001

APPLICATION OF SIGNALIZED INTERSECTION MODELS TO TREATMENT SAMPLE

The conversion dataset consisted of site-years of data for which the intersections were signalized. The number of crashes for these site-years was compared to that predicted by a model calibrated for signalized intersections. The purpose was to test if converted intersections in the sample behaved similarly after conversion to other signalized intersections in the model calibration datasets in terms of the relationship between crashes and traffic volume.

The results, shown in Table B-35, are promising. Results for total, right angle and rear-end crashes perform well. It could be concluded with caution that the close correspondence between the observed and predicted crashes using the signalized reference group model is ample indication that converted intersections in the sample behave similar to other signalized intersections in terms of the relationship between crashes and traffic volume.

Table B-35. Crashes at 4-Leg intersections after conversion.

Crash Type	Basis for after period crashes	Crashes in after period
Right-angle	Observed	326
	Estimated by signalized reference group model	383
Rear-end	Observed	695
	Estimated by signalized reference group model	679
All	Observed	1496
	Estimated by signalized reference group model	1592

These results provide some evidence that the models can be used as part of a procedure for conducting an engineering study to assess whether or not a contemplated signal installation is warranted. In this, an empirical Bayes estimate of the expected number of crashes without signalization is compared to the number of accidents expected with signalization, the latter estimated from a regression model for signalized intersections. The elements of this procedure are presented next.

PROCEDURE FOR ESTIMATING THE SAFETY BENEFIT OF A CONTEMPLATED CONVERSION OF AN EXISTING RURAL STOP-CONTROLLED INTERSECTION TO SIGNALIZED CONTROL

The objective is to provide designers and planners with a tool to estimate the change in accident frequency expected with the conversion of a rural stop-controlled intersection to signalized control.

For this approach, which is similar to one developed for urban signalized intersections[1], a Safety Performance Function (SPF) representative of the existing stop-controlled intersection is required. This will require that one exists for the jurisdiction or that data are available to enable a recalibration of a model calibrated for another jurisdiction. The SPF would be used, along with the intersection's accident history, in the empirical Bayes procedure to estimate *the expected accident frequency with the status quo in place*, which would then be compared to *the expected frequency should a conversion to signalized control take place* to estimate the expected benefit.

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[1] McGee H, Persaud B. and S. Taori. "Crash Experience Warrant for Traffic Signals". National Cooperative Highway Research Program (NCHRP) Report 491, Transportation Research Board, 2003.

The *expected frequency should conversion to signalized control take place* is estimated from an SPF representative of signal controlled intersections in the same jurisdiction. Again, this will require that one exists for the jurisdiction or that data are available to enable a recalibration of a model calibrated for another jurisdiction. The approach is convenient, in that a comprehensive set of accident modification factors, which would be required for a large number of conditions, including AADT levels, is simply not available and is difficult to obtain.

Overview of the approach

Step 1:

Assemble data and accident prediction models for rural stop-controlled and signalized intersections. For the past, say, five years,

1. Obtain the count of total, right-angle and rear-end accidents which occurred at the intersection of interest,
2. For the same time period obtain or estimate the average AADTs on the major and minor roadways,
3. Estimate the average AADTs on the major and minor roads that would prevail for the period immediately after conversion to signal control,
4. Assemble required accident prediction models for rural stop-controlled intersections and rural signal controlled intersections. If the models cannot be assumed to be representative of the jurisdiction, they must be recalibrated using data from a sample of intersections representative of that jurisdiction. At a minimum, data for at least 10 intersections with at least 60 accidents is needed. The re-calibration multiplier is simply the number of crashes recorded in the sample divided by the number of crashes predicted for the sample by the model.

Step 2:

Use the EB procedure with the data from Step 1 and the stop-controlled intersection model to estimate the expected annual number of right-angle, rear-end and “other” accidents that would occur without conversion. (The EB estimate for “other” crashes is the EB estimate for total minus the sum of the EB estimates for rear end and right angle crashes.)

Step 3:

Use the signalized intersection models and the volumes from Step 1 to estimate the expected number of rear-end, right-angle and other crashes that would occur if the intersection were converted. (The estimate for “other” is the estimate for total minus the sum of the estimates for rear-end and right-angle.)

Step 4:

Obtain for rear-end, right-angle and “other” crashes, the difference between the estimates from Steps 2 and 3 and check that any estimated reduction in right-angle crashes is statistically significant.

Step 5:

Applying suitable severity weights and dollar values for rear-end, right-angle, and other crashes, obtain a net benefit of signal installation.

Step 6:

Compare against the cost, considering other impacts if desired, and using conventional economic analysis tools. How this is done, and in fact whether it is done, is very jurisdiction-specific and conventional methods of economic analysis can be applied after obtaining estimates of the economic values of changes in delay, fuel consumption and other impacts.

Example

A rural four-leg stop-controlled intersection with data from January 2001 to December 2005, is being considered for signal installation. Data and results of the analysis are displayed in Tables 1-3.

Example Step 1:

Assemble data and crash prediction models

a) Crash data – The counts of total, right angle and rear-end crashes in each year of the analysis period are shown in the second row of Tables B-36 through B-38.

b) AADT data – Entering AADTs for the major and minor roads for each year are estimated for each year using suitable methods applied locally and are entered in the 3rd and 4th rows of Tables B-36 through B-38. It is recognized that actual counts are typically not available for each year; however, in most jurisdictions trend factors are available that could be applied to estimate AADTs for each year. A separate process can be used to provide the best estimate of the AADT after signalization, considering traffic that might be generated to the intersection in the future. In the absence of such an estimate, the AADT expected after signalization can be assumed to be same as that in the last year.

c) Crash prediction models – For this example, these are required for rural 4-leg stop controlled intersections for each of the years 2001 to 2005 and for rural signalized 4-leg intersections for the last full year. Ideally each jurisdiction would have its own set of applicable models. The models adopted for this example are shown below in Tables B-39 and B-40.

Table B-36. Summary of results for total crashes.

1) Year (y)	2001	2002	2003	2004	2005
2) Crashes in year (X)	4	9	8	14	7
	Sum = $\mathbf{X_b}$ = 42				
3) MAJAADT	24000	25500	26000	28000	30000
4) MINAADT	2500	2550	2650	2800	3000
5) Recalibrated $\alpha \times 10^{-4}$	1.03	1.05	1.07	1.09	1.11
6) Parameter K	0.483	0.483	0.483	0.483	0.483
7) Model Prediction $E\{\kappa_y\}$	6.3	6.8	7.1	7.9	8.7
8) $C_{i,y} = E\{\kappa_y\}/ E\{\kappa_{2001}\}$	0.72	0.78	0.82	0.90	1.00
9) Comp. Ratio for period	$\sum C_{i,y} = 4.22$				
10) Expected annual crashes without signalization (and variance) in 2005	$\kappa(2005) = C_{i,2005}(1/K+ \mathbf{X_b})/((1/K)/E\{\kappa_{2005}\}+\sum C_{i,y})$ = 1.00(1/0.483+42)/((1/0.483)/8.7+4.22) = 9.9 $Var[\kappa(2005)] = (C_{i,2005})/(1/K+ \mathbf{X_b})/(1/K/ E\{\kappa_{2005}\}+\sum C_{i,y})^2$ $= (1.00)(1/0.483+42)/(1/0.483/8.7+4.22)^2$ = 2.2				
11) Expected annual crashes after signalization (and variance) in 2005	$E\{\kappa_{2005}\}=0.010245(30000^{0.443})(3000^{0.2237})$ = 5.9 $Var[E\{\kappa_{2005}\}]= 0.373(5.9)^2$ = 13.0				

Table B-37. Summary of results for right-angle crashes.

1) Year (y)	2001	2002	2003	2004	2005
2) Crashes in year (X)	2	4	5	7	4
	Sum = $\mathbf{X_b}$ = 22				
3) MAJAADT	24000	25500	26000	28000	30000
4) MINAADT	2500	2550	2650	2800	3000
5) Recalibrated $\alpha \times 10^{-4}$	0.330	0.337	0.343	0.350	0.357
6) Parameter K	1.128	1.128	1.128	1.128	1.128
7) Model Prediction $E\{\kappa_y\}$	2.5	2.6	2.8	3.1	3.4
8) $C_{i,y} = E\{\kappa_y\}/ E\{\kappa_{2001}\}$	0.72	0.77	0.81	0.90	1.00
9) Comp. Ratio for period	$\sum C_{i,y} = 4.19$				
10) Expected annual crashes without signalization (and variance) in 2005	$\kappa(2005) = C_{i,2005}(1/K+ \mathbf{X_b})/((1/K)/E\{\kappa_{2005}\}+\sum C_{i,y})$ $= 1.00(1/1.128+22)/((1/1.128)/3.4+4.19)$ $= 5.1$ $\mathrm{Var}[\kappa(2005)] = (C_{i,2005})/(1/K+ \mathbf{X_b})/(1/K/ E\{\kappa_{2005}\}+\sum C_{i,y})^2$ $= (1.00)(1/1.128+22)/(1/1.128/3.4+4.19)^2$ $= 1.2$				
11) Expected annual crashes after signalization (and variance) in 2005	$E\{\kappa_{2005}\}=0.018369(30000*3000)^{0.1976}$ $= 0.7$ $\mathrm{Var}[E\{\kappa_{2005}\}]= 0.511(0.7)^2$ $= 0.25$				

Table B-38. Summary of results for rear-end crashes.

1) Year (y)	2001	2002	2003	2004	2005
2) Crashes in year (X)	1	2	3	4	0
	Sum = $\mathbf{X_b}$ = 10				
3) MAJAADT	24000	25500	26000	28000	30000
4) MINAADT	2500	2550	2650	2800	3000
5) Recalibrated $\alpha \times 10^{-4}$	0.01	0.01	0.01	0.01	0.01
6) Parameter K	0.726	0.726	0.726	0.726	0.726
7) Model Prediction $E\{\kappa_y\}$	1.2	1.4	1.4	1.6	1.8
8) $C_{i,y} = E\{\kappa_y\}/ E\{\kappa_{2001}\}$	0.68	0.75	0.79	0.89	1.00
9) Comp. Ratio for period	$\sum C_{i,y} = 4.11$				
10) Expected annual crashes without signalization (and variance) in 2005	$\kappa(2005) = C_{i,2005}(1/K+ \mathbf{X_b})/((1/K)/E\{\kappa_{2005}\}+\sum C_{i,y})$ $= 1.00(1/0.726+10)/((1/0.726)/1.8+4.11)$ $= 2.3$ $\mathrm{Var}[\kappa(2005)] = (C_{i,2005})/(1/K+ \mathbf{X_b})/(1/K/ E\{\kappa_{2005}\}+\sum C_{i,y})^2$ $= (1.00)(1/0.726+10)/(1/0.726/1.8+4.11)^2$ $= 0.48$				
11) Expected annual crashes after signalization (and variance) in 2005	$E\{\kappa_{2005}\}=0.000812(30000^{0.5791})(3000^{0.2718})$ $= 2.8$ $\mathrm{Var}[E\{\kappa_{2005}\}]= 0.505(2.8)^2$ $= 3.96$				

Table B-39. SPFs for California stop-controlled intersections (4-leg with 2 lanes on major approach).

	Total	**Right-Angle**	**Rear-End**
Model	1	1	2
LN(α) **(standard error)**	-9.1488 (0.554)	-10.2351 (0.9337	-13.6527 (0.7938)
β₁ **(standard error)**	0.7191 (0.060)	0.5707 (0.099	1.4201 (0.088)
β₂ **(standard error)**	0.4813 (0.028)	0.6978 (0.047	0.1857 (0.041)
Dispersion, K	0.483	1.128	0.726
Model 1: $E\{\kappa\} = \alpha(Maj)^{\beta_1}(Min)^{\beta_2}$	**Model 2:** $E\{\kappa\} = \alpha(Maj+Min)^{\beta_1}\left(\frac{Min}{Maj+Min}\right)^{\beta_2}$		

Table B-40. SPFs for California signalized intersections (4-leg).

	Total	**Right-Angle**	**Rear-End**
Model	1	2	1
LN(α) **(standard error)**	-4.0402 (0.1267)	-2.6105 (1.1337)	-6.7249 (1.4141.)
β_1 **(standard error)**	0.4430 (0.1297)	0.1976 (0.0655)	0.5791 (0.1425)
β_2 **(standard error)**	0.2237 (0.0520)		0.2718 (0.0572)
State **(standard error)**	CA = -0.5407 (0.1402) Minnesota = 0	CA = -1.3866 (0.1725) Minnesota = 0	CA = -0.3903 (0.1687) Minnesota = 0
Dispersion, K	0.3733 (0.561)	0.5110 (0.0931)	0.5051 (0.0793)
Model 1. $Acc/yr = \alpha(Major\ AADT)^{\beta_1}(Minor\ AADT)^{\beta_2} e^{state}$ **Model 2.** $Acc/yr = \alpha(Major\ AADT \text{ x } Minor\ AADT)^{\beta} e^{state}$			

It is recommended that these models be recalibrated for each jurisdiction and for each year of the analysis period. To do so requires yearly crash counts and AADTs for a sample of intersections in the jurisdiction that are typical of those that tend to be considered for signal installation. The default base model is used to estimate crashes each year for each intersection in the sample. For each year, the sum of the observed counts divided by the sum of the model estimates gives a calibration factor that is applied to the model to obtain a recalibrated value of *α*. These recalibrated values of α for the current illustration are shown in row 5 of Tables B-7 through B-9. A similar recalibration process can be done to adjust the *α* parameter for the signalized intersection model for the year 2005. In this example, it is assumed that this adjustment was not necessary.

Example Step 2:

a) Estimate the expected number of crashes per year using the recalibrated SPFs. For example, for 2001,

$$E\{\kappa_{2001}\}_{total} = (0.000103)(41302)^{0.7191}(3596)^{0.4813} = 6.3$$

$$E\{\kappa_{2001}\}_{right\ angle} = (0.000033)(41302)^{0.5707}(3596)^{0.6978} = 2.5$$

$$E\{\kappa_{2001}\}_{rear\ end} = (0.000001)(41302+3596)^{1.4201}(3596/(41302+3596))^{0.1857} = 1.2$$

These estimates are shown in row 7 of Tables B-36 through B-38.

b) Calculate the comparison ratio ($C_{i,y}$) of the model estimate for a given year divided by the model estimate for 2005. These ratios are shown in row 8 of Tables B-36 through B-38 and summed in row 9.

c) Using the values in the previous rows and the formula show in the tables estimate the expected annual number of crashes without signalization (and variance) for the last year (2005). These values are shown in row 10 of Tables B-36 through B-38.

Example Step 3:

Use the signalized intersection SPFs (reproduced in Table B-41) to estimate the number of crashes per year if the intersection were signalized using the expected annual AADTs after signalization. For this example, the year 2005 is used to correspond with the estimates from Step 2 and it was assumed that a recalibration of the default base models were not required.

Also estimate the variance of the estimate as:

$$\mathrm{Var}[E\{\kappa_{2005}\}] = K(E\{\kappa_{2005}\}^2)$$

Table B-41. SPFs for Signalized Intersections (4-leg).

	All	**Right-Angle**	**Rear-End**
Model	1	2	1
LN(α) **(standard error)**	-3.4995 (0.1267)	-3.9971 (1.1337)	-7.1152 (1.4141)
β_1 **(standard error)**	0.4430 (0.1297)	0.1976 (0.0655)	0.5791 (0.1425)
β_2 **(standard error)**	0.2237 (0.0520)		0.2718 (0.0572)
Dispersion, K	0.3733 (0.561)	0.5110 (0.0931)	0.5051 (0.0793)
Model 1. Acc/yr = $\alpha(\text{Major AADT})^{\beta 1}(\text{Minor AADT})^{\beta 2}$ **Model 2.** Acc/yr = $\alpha(\text{Major AADT*Minor AADT})^{\beta 1}$			

The results are in the row 11 of Tables B-36 through B-38.

Example Step 4.

<u>Step 4a</u> – Estimate the change in crashes per year if the intersection was converted to a signalized intersection as follows:

Total = 9.9 – 5.9 = 4.0 (decrease)

Right-angle = 5.1 – 0.7 = 4.4 (decrease)

Rear-end = 2.3 – 2.8 = -0.5 (increase)

Other = (9.9-5.1-2.3) – (5.9-0.7-2.8) = 0.1 (decrease)

Step 4b – Test for significance of the changes in major crash types. If there is a net decrease in total crashes, check that there is an expected decrease in right angle crashes and that this change is statistically significant. If there is a net increase in total accidents, check that there is an expected increase in rear-end accidents and that this change is statistically significant. If the expected changes do not materialize or are not statistically significant at the 10% level, then safety should not be used in evaluating the impacts of signalization.

In this case there is net decrease in total accidents and an expected decrease of 4.4 right-angle accidents/year. The variance of this change in right-angle accidents is equal to the sum of the variances of the two numbers that yielded this value.

$$\mathrm{Var}\{\kappa(2005)_{\text{right angle}}\} + \mathrm{Var}\{\kappa(2005)_{\text{signal/right angle}}\} = 1.20+0.25 = 1.45$$

The standard deviation is 1.2, which means that the decrease of 4.4 is statistically significant since a value of zero lies outside of 1.64 standard deviations (for a 10% significance level).

Example Step 5

Consider the relative costs of right-angle, rear-end and other crashes.

Crash cost data is available from FHWA report number FHWA-HRT-05-051 “Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometrics”. The report provides the mean and standard error of the comprehensive cost per crash for various crash types disaggregated by various combinations of maximum severity level on the KABCO scale and also disaggregated by speed limit (>=50, <=45). The disaggregation by speed limit was an attempt to control for urban versus rural environment, a variable not available in the data used to derive the cost estimates. The analysis used estimates for the >=50 mph speed category to reflect the rural conditions of the treatment sites.

The unit crash costs used for this example are reproduced in Table B-42.

Table B-42. Unit crash costs for all severities (standard errors in parentheses).

Control Type	Right Angle Cost	Rear End Cost	Other Cost
Signal	$75,197 ($7,747)	$32,544 ($6,219)	$75,197 ($7,747)
Stop Sign	$96,942 ($25,619)	$10.008 ($4,027)	$96,942 ($25,619)

Using these costs and the expected crash frequencies in 2005 from Tables B1 through B-3, the estimated net annual benefit of signal installation at this intersection is estimated.

Annual Cost Without Signalization

= 5.1($96,942)+2.3($10,008)+(9.9-5.1-2.3)($96,942)

= $759,778

Annual Cost With Signalization

= (0.7)($75,197) + (2.8)($32,544)+(5.9-0.7-2.8)($75,197)

= $324,234

Annual Economic Benefit From Signalization

= $759,778 - $324,234

= $435,544

Example Step 6

Compare cost of signal installation against the benefits, considering operational benefits as well. How this is done is very jurisdiction specific and conventional methods of economic analysis can be applied after obtaining estimates of the economic values of changes in delay, fuel consumption and other impacts. Traffic engineering studies can be conducted and tools such as simulation can be used to estimate the changes in operational parameters, such as delay times, stops, fuel consumption, emissions, etc.

DISCUSSION AND CONCLUSIONS

The data collected and analyzed for this study clearly show that the safety benefit of signalizing an un-signalized intersection is a function of the crash history by crash type, the traffic entering the intersection on the major and minor approaches, and whether the intersection is a 3-legged T-intersection or a conventional 4-legged intersection. The available data indicated that total crashes can be reduced by signalizing an intersection with certain levels of crash frequency and traffic volumes, although individual intersections may yield contrary results.

An economic analysis reaffirms the benefits of signalization, where warranted. In particular, benefits of signalization are to be expected where the ratio of right-angle to rear-end crashes is high.

A procedure for estimating the safety benefits of a contemplated signal installation has been developed and presented and should be consider for application to supplement procedures used to decide if a signal installation meets MUTCD or other warrants.

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